

Aesthetic Electronics: Designing, Sketching, and Fabricating Circuits through Digital Exploration

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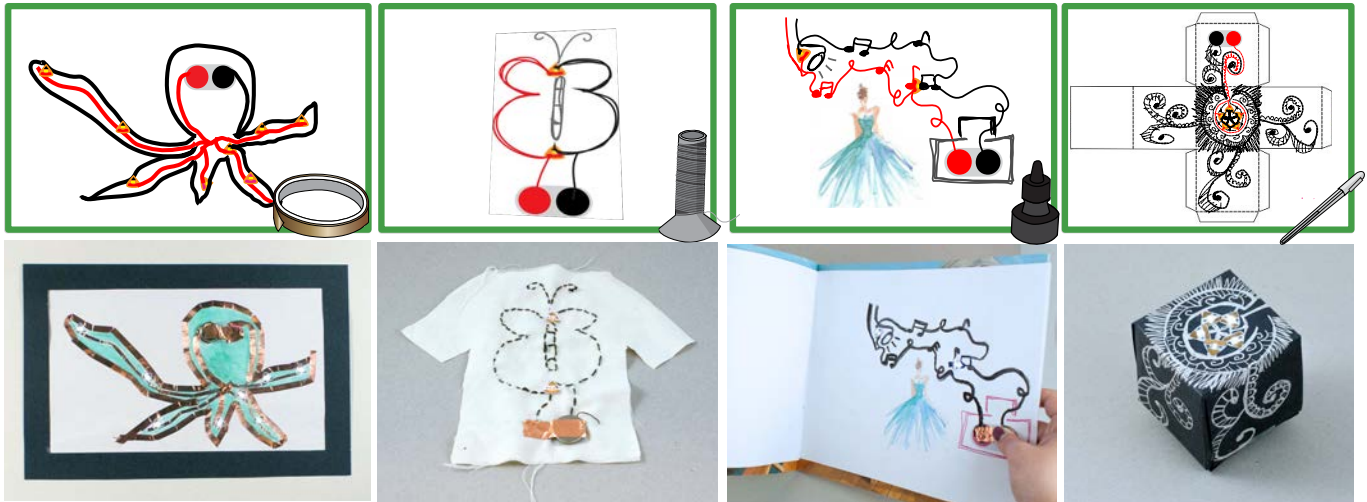


Figure 1. Sketched digital circuits (top), and fabricated circuits (bottom) created through various craft mediums: a) copper tape painting on paper, b) sewn conductive thread on fabric, c) painted graphite ink as interactive illustration, and d) decorative silver ink to ornament physical objects.

ABSTRACT

As interactive electronics become increasingly intimate and personal, the design of circuitry is correspondingly developing a more playful and creative aesthetic. Circuit sketching and design is a multidimensional activity which combines the arts, crafts, and engineering broadening participation of electronic creation to include makers of diverse backgrounds. In order to support this design ecology, we present Ellustrate, a digital design tool that enables the functional and aesthetic design of electronic circuits with multiple conductive and dielectric materials. Ellustrate guides users through the fabrication and debugging process, easing the task of practical circuit creation while supporting designers’ aesthetic decisions throughout the circuit authoring workflow. In a formal user study, we demonstrate how Ellustrate enables a new electronic design conversation that combines electronics, materials, and visual aesthetic concerns.

Author Keywords

design tool; sketching circuits; fabrication

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION

The landscape of electronics is rapidly changing. Devices are becoming exponentially smaller, requiring electronic circuits to be printed directly on a device’s housing and on ultra-thin wearables [19, 14]. As such, new designs must blend functional and aesthetic design variables. Echoing the Radical Atoms vision, such designs compel “new material design principles” that unify these design variables in order to “treat objects as homogeneous entities with the ability to change their properties” [12].

In this paper, we introduce the term *Aesthetic Electronics* to describe a class of electronics that foregrounds both functional electronics and visual aesthetics as interrelated design variables. In such electronics, aesthetic characteristics (e.g. form and symmetry) affect how designers choose materials and make marks; in tandem, these choices affect electrical design variables (e.g. resistance, capacitance, and inductance). In practice, Aesthetic Electronics can enhance the making experience to engage various crafting and art practices and contextualize circuit designs (Figure 1).

This work focuses on the creation of a subset of Aesthetic Electronics - *Aesthetic Circuits* which explores electrical traces, or elements which connect electronic components, as a site of creativity. Contrasted with the broader field

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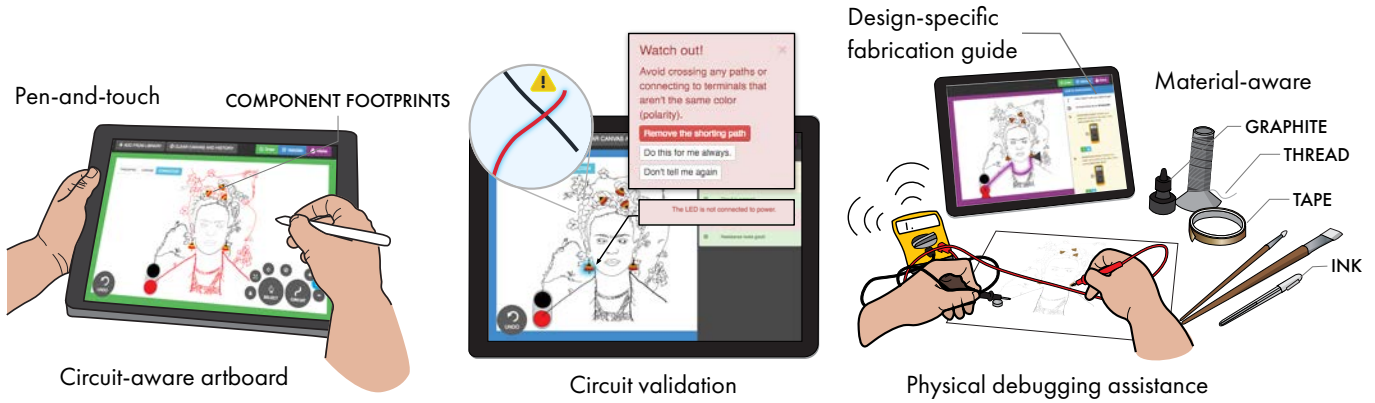


Figure 2. Illustrate circuit authoring process. The user sketches a digital design on a circuit-aware artboard. The tool validates the circuit and the user corrects electrical errors if necessary. Custom fabrication instructions are produced to guide the user in making a physical circuit.

of Aesthetic Electronics, where active physical devices (i.e. capacitors, strain gauges, speakers) can be made with aesthetic value, Aesthetic Circuits focuses on the design of the passive electrical traces. Traces are currently one of the most restricted design element in circuit design tools, resulting in circuit layouts with linear, efficiency-focused designs. While circuit authoring tools such as 123D Circuits and Fritzing [1] enables creative designs through the large and well-documented library of electronic components, even these entry-level tools still favor the traditional straight-line aesthetic for routing the final printed circuit board layout. While this tried-and-true layout method is extremely valuable, it also limits how electronics and circuits are viewed as something pedantic instead of creative. Despite the tremendous benefits brought to circuit creation, these tools have remained restricted to a physical classroom setting [26, 25].

Creating Aesthetic Electronic designs requires a unique fluency over the affordances and electrical properties of materials. We enable Aesthetic Circuit design through Ellustrate, our digital design and fabrication assistance tool (Figure 2). Ellustrate, leverages a process known as “sketching circuits”, a design and fabrication process that enables the creation of physical circuits with craft materials [25]. As a natural and intuitive process, sketching is a shared skill amongst professional engineers, designers, makers and artists. Moreover, the circuit sketching process has been shown to increase participation in electronic design from diverse populations, remove negative stigma associated with circuits, and motivate early learners [26]. Various research fields have taken notice of the circuit sketching trend as well, creating various conductive materials (i.e silver, graphite, copper) that can be applied on paper in ways similar to a regular pen [2, 28].

While the usability of conductive materials has enabled many creative crafting projects, we believe the complexity and creativity in electronic craft can be further augmented by providing two critical elements – a digital circuit-design sandbox and assistance for physical fabrication and debugging. We introduce Ellustrate, an aesthetic circuit authoring process and tool illustrated in (Figure 2). Our main contributions are:

- a review of best practices for Aesthetic Circuits fabrication and debugging based on formative studies and expert surveys,

- a natural sketching design interface which balances concerns of electronic rules and expressive visual design,
- a fabrication tool that aids users in developing physical skills, specifically, fabricating and debugging physical Aesthetic Circuits,
- a formal user evaluation that provides insights into the Aesthetic Circuit design space.

Ellustrate differs from most circuit design tools in a number of ways summarized by Figure 3, and supports Aesthetic Circuit sketching as a step towards broadening the definition of electronic design to invite participation from practitioners of diverse backgrounds.

RELATED WORK

We base our work on established research on nontraditional circuits and electronics, as well as relevant digital tools.

Sketching electronics on familiar materials

By fabricating electronics on a familiar material, like paper, users can explore electronic design using a previously held skill set. Augmenting such common everyday materials with power, lights, and motions has been shown to introduce a sense of wonder that resonates with people of diverse ages and backgrounds [5, 24, 26, 25]. Crafting have shown to be a powerful technique in STEM education that encourages interdisciplinary participation and further democratizes making and science education [25]. Furthermore, the role of these materials in everyday life has been shown to be a natural platform for story-telling with electronics [13]. As such, incorporating familiar materials in circuits has altered the design

	Adobe Illustrator	Eagle	123D Circuits	Ellustrate
Visual Design	✓	–	–	✓
Electronics Library	–	✓	✓	✓
Routing Guidance	–	✓	✓	✓
Simple Validation	–	✓	✓	✓
Multimaterial Support	–	–	–	✓
Multilayer Layout	–	✓	–	–
Autorange	–	✓	–	–

Figure 3. A comparison of design tool features. Ellustrate provides coverage for both visual design and circuit design concerns.

landscape leading to more natural, organic, and novel circuit layouts. As more conductive and non-conductive materials develop, so does the complexity of understanding the unique electronic intricacies of each material [10]. Ellustrate aims to support the circuit sketching practice by providing a digital design tool that supports working with different materials and encourages an aesthetic exploration of circuit designs.

Digital sketching tools

Since sketching is such an important element of early stage design, many digital tools have been created to facilitate this process. These tools transform sketches into prototypes of a final design by decomposing and recognizing domain-specific symbols and lines. In SILK and SATIN, Landay et al. and Hong et al. investigate sets of software support functions for sketching user interfaces, website design, and simple logic circuits [11, 15]. The two tools generate a final design by “cleaning up” imperfections in the hand-drawn sketches – short, overlapping lines are combined, strokes are straightened, and imperfect symbols of logic gates are corrected. The traces between the elements are often reduced to the the shortest straight path possible. To explore the creative value in the sketches, Ellustrate does not correct or reduce the electrical traces (except for electrical functional reasons).

Digital design tools for physical designs

Digital tools have revolutionized the hardware prototyping process by allowing users to iterate on a digital design before creating the physical version through simulations of the electronic and mechanical properties. Digital tools provide educational guidance for various aspects of the physical making process. In PaperPulse, users can program the behavior of a microcontroller, print out the design using a conductive ink printer, and fabricate the design with instructions generated by the tool [27]. In d.tools, designers can design and iterate hardware interactions using statecharts to control plug-and-play hardware (i.e. slider, LED) [8]. Within the AutoDesk CircuitScribe design tool, users can sketch and simulate circuit designs. The design can then be printed on a piece of paper and traced over with a silver pen [1]. Ellustrate expands upon this work by 1) implementing a sketching platform for pen-and-tablet to emulate a more natural sketch interaction, 2) augmenting the available electronic component footprints and materials library to support a diverse set of circuit components’ footprints, and 3) integrating fabrication and debugging guidance to lower the barrier of entry for users with little to no circuit background.

FORMATIVE INTERVIEWS

As much as existing circuit sketching enables creative exploration of circuit designs, the tacit knowledge involved in the process could be a challenge to beginners in the craft. To identify the common difficulties that users encounter in the early stage of circuit design, we performed a series of formative user studies and interviews.

To learn about opportunities for supporting circuit sketching and fabrication with a digital design tool, we interviewed three circuit educators and seven potential users. Educators were experienced in teaching students with no prior electronic

design knowledge from different domains: an introductory circuits Massive Open Online Course (MOOC), Maker Faire workshops, and circuit sketching workshops. The potential users recruited were university students with little to no circuits background, but with varying levels of design experience. Utilizing a think-out-loud protocol, we asked four interviewees to design a circuit with two different colored markers to study possible visual styles, and three interviewees to design and fabricate three simple LED* circuits with copper tape (eliciting help from the interviewer as needed) to study potential fabrication and debugging problems. We note two major observations that informed the design of our system.

Immediate feedback and validation

In hardware design, designers encounter two main types of error – electronic design rule violations (i.e. electrical shorting), and functional errors (i.e. parallel LEDs routed in series). They are analogous to the classifications of syntax and semantic errors in software, respectively. Digital tools are immensely useful when it comes to catching syntax errors within a circuit design, but few hardware design tools provide design feedback in a way that is accessible to early learners. All experts we interviewed agreed that a electrical design check as immediate feedback during the design process would greatly benefit learners. Existing literature supports their opinions [9, 6]. Our circuit learners reported having more confidence in their subsequent design decisions if positive and negative feedback were given immediately, especially in the beginning of the design process. Although Ellustrate is not structured as a tool specific for learning, it does aim to build lasting good electrical design habits. During the circuit sketching process, we observed that the design rule that most users have trouble with was creating a layout that avoids electrical shorts.

Expert knowledge and guidance

Unfortunately, assistance fabricating or debugging circuits is not provided in most circuit design tools. Such instruction largely remains restricted to in-person classroom/workshop settings[25]. We feel that providing a debugging and fabrication guide is crucial to achieving our goal of empowering designers. One major difference in fabrication that we observed between experts and entry level circuit makers was the ability to modularize their circuits into small, individually-testable sections in a way that might minimize the chances of error propagation. We formulated expert advice into rational steps that users can follow to fabricate their design. Furthermore, experts articulated the need for in-situ debugging advice or else risk potentially overloading a learner with too much information.

AESTHETIC CIRCUIT DESIGN OBJECTIVES

Our formative interviews and preliminary investigations identify four primary features that an Aesthetic Circuit design tool should include in order to balance electrical, material, and visual design principles:

*Chibitronics LED stickers

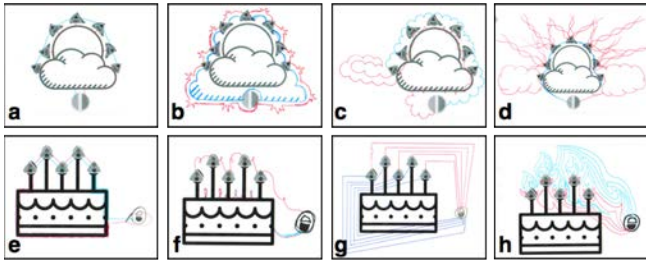


Figure 4. Designs from the formative study drawn with non-conductive ink pens on paper, with red lines for power and blue line for ground. Using either a sun and clouds (a-d) or a birthday cake (e-h) as an artistic scaffold, the complexity of the interviewees’ circuits varied considerably

1. Freeform circuit drawing tool

The design of electrical traces that possess both electrical function and aesthetic properties is possibly the most critical task in creating Aesthetic Circuits. In traditional circuit design tools, routing of simple circuits can be assisted by autotrace – a algorithm-driven process that determines the shortest and most efficient paths to connect electronic components on a given circuit board [7]. Autotrace creates routing that minimizes board space and noise, but does not provide any aesthetic freedom. On the other hand, the design of Aesthetic Circuits, although still retaining the need for functionality, has less of a concern in minimizing board space and noise. Therefore, a digital tool for Aesthetic Circuit design needs to provide the freedom of creating artistic drawing but provide enough restraints to simultaneously ensure electrical function. Just as breadboarding results in “wire nests”, sketching circuits can quickly become a complex circuit routing puzzle especially when combined with visual design. When the electronic components are placed in a nonlinear fashion, powering all of them without shorting the circuit or creating excessively long traces becomes difficult. In Qi et al, a paper template is provided to workshop participants to guide them in placing copper tape [25]. While this method is highly effective in aiding participants in creating functional circuits, it limits creativity in visual design [25]. Within Ellustrate, users are encouraged to explore and iterate different placements of electronic components and traces to optimize the balance between visual design and circuit functionality.

2. Electronics and materials library

Footprint and electronic properties (i.e. turn on voltage, maximum current) are important criteria in any circuit design. Understanding these properties is essential to creating visually pleasing and functional circuit design. However, this vital information, which is readily available in any circuit design software (i.e. Eagle, Cadence, 123D Circuits), is not provided in any visual design software. This greatly limits the ability of the designer to create a functional circuit while exploring the visual elements of an electronic component’s footprint. In addition to the lack of electronic libraries, users that create physical circuits with nontraditional materials such as silver paint, graphite, and conductive thread face additional difficulties fabricating traces with varying, uncharacterized, and relatively high resistance materials (compared to traditional copper traces). These long, highly resistive traces of-

ten cause problems that are invisible to designers with little circuit design experience [3].

3. Fabrication and debugging guidance

The physical fabrication of the designed circuit is a difficult step in the creative process, as discovered in the Qi et al study [25] and our formative user study. Solving hardware problems, which often requires probing to locate the issue, can seem like a “dark art” to early circuit learners and heavily relies on tacit knowledge. In a workshop setting, guidance is provided to the participants to fabricate the circuit and debug any problems [25]. However, in-person guidance is not easily scalable. Digital tools that provide physical guidance have been shown to improve engagement with techniques and processes [29]. Within Ellustrate, fabrication steps are provided in a step-by-step guideline, incorporating the modular fabrication process recommended by experts, whereas debugging guidance is provided in an expandable menu for users to access as needed.

4. Electrical validity

Circuit validation is a large and complex field of study [23]. To focus our contributions on circuit assistance design, we limit the scope of our circuit validation to deal with circuits consisting of only LEDs, resistors, and batteries. These components enable a high level of expressivity without being overly computationally intensive for the digital tool. The following design pattern can be extended to the more multifaceted RLC (Resistance, Inductance, Capacitance) circuit or circuits with integrated chips [21]. The most common task in electronic circuit design is the ability to connect components to sources of current. Most connections are modeled as perfect conductors, having a negligible resistance. As conductive materials enter this landscape, we encounter the need to represent the resistance of each connection since its resistance is no longer negligible [4].

Design objectives

To support these features, an Aesthetic Circuit design tool should ensure:

- **Electrical Validity:** circuits are electrically valid and prevent common mistakes;
- **Legibility:** complex circuit designs remain legible for easy repair and sharing;
- **Fabricability:** circuit designs are fabricable with the available materials with their given electrical characteristics;
- **Craft:** allow mechanical processes to interact with a material such that the material exists in a “continuum of [possible] states”[20]; and
- **Expressivity:** users are able to freely express and explore their creative style and vision.

These objectives provide users with a suite of components and guidance to design and fabricate a physical circuit.

SYSTEM DESIGN

The structure of Ellustrate follows the model-control-representation (physical and digital) (MCRpd) [30]. Ellustrate provides a digital representation of the physical system

– the circuit design and the fabrication process – and allows users to iterate their design and modify their fabrication.

The Illustrate tool was designed for users with familiarity with vector graphics and built as a web application portable to several form factors; we use an Apple iPad Pro and Apple Pencil, chosen to emulate a pen and paper design environment. Illustrate uses the paper.js vector graphics scripting framework [16] which enables common vector editing operations and backwards compatibility with vector graphics applications. Interactions follow noun-verb drawing application conventions (i.e., click on icon, carry out action). At a high level, the tool exposes to users two operations: laying down components, and making marks representing different conductive materials to connect components.

We chose to restrict vector operations to path drawing and affine transformations of objects. This was largely motivated by an interest in reducing the tool’s complexity and exposing the hand-drawn line, as opposed to “perfect” machine curves, to achieve a sketching-with-pen feel.

SVG representation

Canvas elements are encoded as Scalable Vector Graphics (SVG), encoding the element name with a specialized prefix denoted by the following hierarchical scheme:

- **1° Illustrate Header (EL):** Used to demarcate the topmost layers of an SVG file that should be processed.
- **2° Material channels (e.g. S1 silver-ink)** Used to specify the material used to render marks; this allows marks to be separable to aid with respective fabrication techniques (similar to CMYK channel separation for offset printing).
- **3° Components (CP)** Specifies a set of elements that are conceptually grouped (e.g. LED, \pm terminals, footprint).
- **4° Elementary components** C(N|G|V)(P|B)[T], NC. The (N|G|V) selector designates the accepted polarity of the mark (neutral, ground, or powered). The (P|B) selector specifies whether the conductive element is being modeled as a path or as a blob (closed path). The T suffix is used to mark voltage sources. NC represents non-conductive elements.

This representation allows us to use off-the-shelf SVG editing software to create custom, accurate component footprints and logic specifications. Furthermore, we can readily export/import representations without affecting the artwork.

Circuit representation

One of the largest challenges to extracting a circuit representation is the visual complexity of a simple sketch. Human visual-processing does an excellent job of grouping elements together; however, if we extract a true-to-form graph of a digital sketch, we quickly surpass processing quotas for graph traversal in interactive applications (~30 ms). We capture some of these visual Gestalt mechanisms in our graph extraction procedure using closeness as a grouping criteria to reduce the number of vertices in the graph (Figure 5).

Graph Extraction. At the point when a user finishes drawing their Illustrate circuit, we have an unconstrained number of SVG paths p . Through a set of post-processing steps,

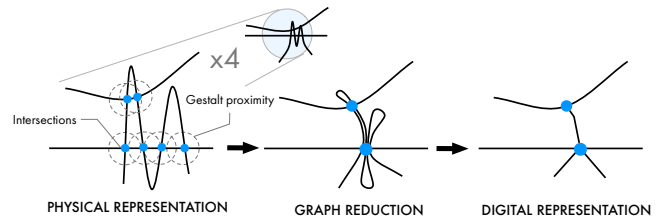


Figure 5. The complexity of a simple scribble adds significant computational complexity to a graph representation of a circuit. Illustrate reduces this complexity by clustering physically-close vertices together.

we extract an undirected graph representation of the circuit as an adjacency list $\langle V, E \rangle$. However, because the direction of electric current takes the path of least resistance, we must first decompose intersecting paths. Let t represent the number of path intersections, s the number of self-intersections, and b the number of blob intersections in an unprocessed design. For each path-intersection and self-intersection, we slice associated paths at their intersection point, yielding at least $2(s + t)$ new paths. Intersections are disregarded if they occur at the start or end of the path, or if the two paths in question are collinear. For each blob intersection, we draw a new path from the associated intersection point on a blob boundary to the blob center, yielding b new paths.

We then populate the adjacency matrix using the start and end of each path as a vertex, encoding each vertex with its position on the canvas. An edge is defined as a connection where two vertices are members of the same path or intersect with another vertex; each edge is encoded with its material composition and cross-sectional area. Dependent on a user’s drawing style, the adjacency matrix contains $|V| = 4(s + t) + 2p + 2b$ and an unconstrained $|E|$.

Optimization step. We use the physical proximity of each vertex to simplify the graph. Vertices which are close together are joined as shown in Figure 5, while duplicate or self-referential edges are removed, reducing the total number of vertices by at least $3(s + t) + b$. This optimization reduces the number of vertices to $s + t + b + 2p$. Contextualizing with respect to sketching, this optimization allows us to work with a 86 vertex graph of the octopus in Figure 1a ($b = 32$, $s = 9$, $t = 17$, $p = 14$) compared to a 196 vertex graph.

Calculating Path Resistance. To provide an accurate model of conductivity for each of these paths, we derive a model from a set of basic electronic rules. In order to determine the resistance of a path between two vertices on a graph, we use breadth-first traversal to enumerate all paths. We collect the traveled edges into a set Q . Each edge e has a previously encoded associated material sheet resistivity ρ_e and sheet thickness t_e , which is simplified to sheet resistance[†] $R_s = \frac{\rho_e}{t_e}$.

We derive the resistance R of a set of edges Q by traversing the edges and summing resistance as derived from cross-sectional area, which follows:

$$R = \sum_{e \in Q} R_s \int_{i=0}^n \frac{1}{w_i} dl \quad (1)$$

[†]Sheet resistance R_s is the measure of resistance of thin films with uniform thickness; conductivity is modeled as the ratio of cross-sectional area and the length of the path.

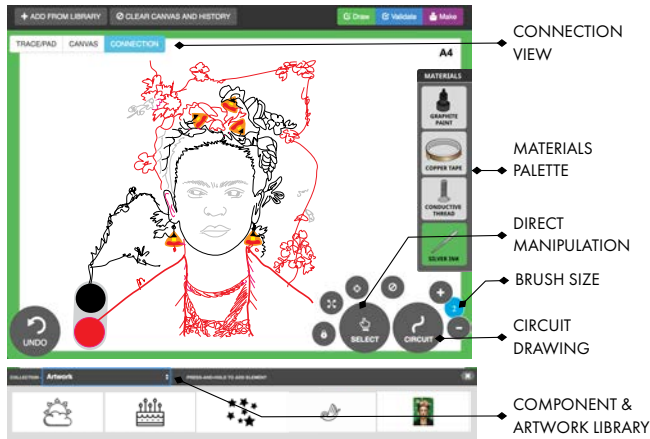


Figure 6. Design step of Ellustrate, which allows a user to sketch a digital representation of a circuit prior to fabrication. The design tool features: connection point highlighting, direct manipulation tools for circuit elements, a tool for sketching traces, and a library of artwork and circuit component footprints.

where n is the euclidean length of an edge, and w_i is the width of the path at offset i . Under this model, a uniform line 2 mm thick and 20 mm in length made with silver ink ($R_s = 0.5$) has a resistance of $5\ \Omega$ whereas a similar mark made with conductive thread ($W = 15\ \mu\text{m}$, $R_s = 2400$) has a resistance of $1.8\ \Omega$.

DIGITAL DESIGN TOOL

In this section we detail how Ellustrate addresses common concerns of traditional circuit design with simple visual rules.

Preventing shorts

Connections must have an adequate resistance to prevent electrical shorts. As such, paths that originate from the voltage source (PWR) cannot make contact with paths connected to ground (GND). As encoded within the SVG, we color-code paths, pads, and other conductive elements with respect to their polarity using conventional color schemes: red (positive), black (negative), or gray (neutral). To prevent shorts, we establish the following visual rule:

Visual Rule I. Connections can only be made from/to similarly-colored (i.e. red|red) elements or from/to neutral elements (i.e. gray).

If a polar connection makes contact with a neutral element, the polarity is propagated to all elements touching the neutral element (Figure 7). Our tool validates this in real-time (detailed in the next section) ensuring that electrically incompatible elements do not exist during draw-time.

Visual Rule II. All polar elements need to be connected to the respective battery pad.

Legibility

In order to aid the user in parsing the circuit of a visually complex design, we introduced two visual mechanisms: a) *glow*, whenever an element is referenced by the tool, a “glow” treatment is applied. Our treatment is a blue shadow with a large blur radius for validation, and a purple overlay for fabrication (Figure 8); b) *thinning*, although not an issue with thin-stroke

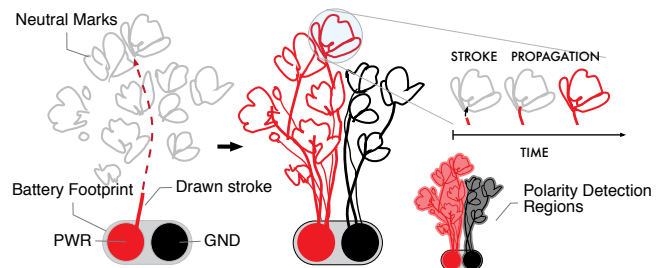


Figure 7. When a user’s stroke intersects existing neutral conductive elements, the polarity of the stroke is propagated and coloring is updated. Polarity detection regions keep track of polar areas of the graph in real-time so as to detect shorts.

mediums, some line weights (e.g., copper tape) occlude electrical connections. When triggering the connection view in Figure 6, design traces are thinned to hairline width and a visual marker is placed on all intersections of the design.

Validation

Validation of the design is presented to users during the design process and once the design has been completed.

Real-time validation

To detect when users accidentally “cross wires,” we implemented real-time polarity collision detection by keeping a map of polar regions on the canvas (Figure 7). This map is represented as a set of polygons constructed from the union of previous conductive elements (in expanded form). If the user draws an incompatible segment inside a polar region, a dialog alerts the user to the error, visually indicates and removes appropriate offending elements (Figure 2, center).

Post-design validation

We run a set of validation rules against the extracted circuit graph to provide users with feedback on the electrical validity and fabricability of their design.

- **BATTERY CHECK.** Verify that a voltage source exists.
- **CONNECTION CHECK.** For all LEDs, verify that there exists a path to ground and a path to power.
- **POWER CHECK.** For each path from PWR to GND, extract the LEDs along the path. Sum the associated voltage-drops of each LED. Check that the voltage drop is not greater than the PWR.
- **RESISTANCE CHECK.** For each path, verify that the resistance is below a threshold.
- **FAB CHECK.** For each path, verify against fabrication-specific constraints (e.g. a warning for long traces might cause a higher chance for fabrication error).

These checks produce error, warning, or success indicators in a validation panel (Figure 2, center); selecting a validation error or warning highlights appropriate elements in the design.

FABRICATION TOOL

Once a circuit has passed digital validation, we provide a set of design-specific fabrication instructions and schematics. For clarity, we describe the fabrication system with respect to silver-ink as the conductive material, but detail which portions of this process are applied to other materials as well.

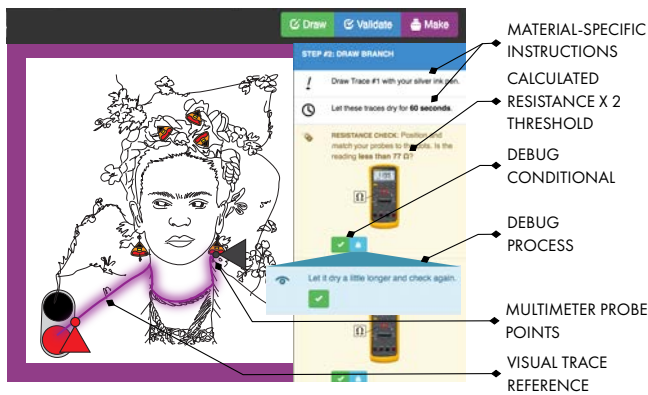


Figure 8. Fabrication phase of Ellustrate, produces design-specific instructions that decomposes a design into a modular fabrication routine. Markers indicate processes such as checking resistance. Conditional instructions allow for users to verify step, or receive debugging assistance.

Design schematics

The Ellustrate design tool outputs a to-scale version of the circuit as an SVG file, which is then printed or transferred onto a circuit substrate (e.g., paper, fabric, etc.). Conductive paths are denoted with dashed magenta lines to indicate where traces should be drawn, while each component footprint is outlined. Lastly, a printable bill-of-materials (BOM) is produced to aid with planning and record-keeping.

Design-specific fabrication instructions

To prevent common fabrication mistakes and to lay out an easy-to-debug circuit, Ellustrate generates instructions that encourage modular fabrication. To decompose the circuit graph, we query our scene graph for all LEDs on the canvas. We then extract the shortest (least resistant) path to power (CVTB) and to ground (CGTB) for each LED, and order these paths by length, which we term *branches*. By fabricating each branch in sequence, a user can modularly test each branch in isolation. We arrived at the following fabrication procedure for circuit building through several pilot iterations with target users. For each instruction, our tool highlights relevant parts of traces and components. For instructions that require the use of a multimeter (MULT), our tool displays an image of the multimeter with the correct dial placement and visually-annotates where multimeter probes should be placed on the circuit (Figure 2, right).

Each instruction set begins by drawing the initial traces originating from the power source with affixing a power source to the circuit. Since a power source is a common requirement for testing each branch, we keep it affixed throughout the process and reduce the number of variables if debugging is necessary.

Battery Instruction Set

1. [Draw] the initial portion of all traces originating from the battery. [Dry].
2. Add the battery.
3. Power Check: For each power-ground path, check that a voltage of approximately 3 V is observed. (MULT)

We then append steps for each branch to the instruction set. Certain steps require confirmation from the user to proceed, and, in the case of a negative confirmation, a debugging step is added to the instruction set and removed once resolved (Figure 8). In addition, material-specific instructions are generated to aid with fabrication. In the case of silver-ink, drying time is affected by the amount of ink deposited by user and can vary from user to user. A drying time of 60 seconds is recommended (indicated by a countdown timer), which is long enough for most cases. Since wet ink has a higher resistance (which might impede circuit function), we also instruct users to test the trace resistance before proceeding.

Branch Instruction Set

1. [Draw] positive and negative traces in branch, [dry].
2. Check resistance of positive trace $\approx 2 \times$ [calculated resistance]. If not, [dry, widen, continuity]. (MULT)
3. Check resistance of negative trace $\approx 2 \times$ [calculated resistance]. If not, [dry, widen, continuity]. (MULT)
4. Place LED, pay attention to orientation; [handling].
5. Check if LED turns on. If not, [press down, go to #2]

Similar instructions are substituted or added for using and debugging different materials, such as:

- [Dry] Material-specific drying times (e.g. BareConductive graphite ink takes longer than CircuitScribe silver ink).
- [Widen] Thickening traces for higher resistance.
- [Handling] For circuit stickers, ensuring that adhesive pads are ink-free, avoiding removing stickers from paper, not touching adhesive side.
- [Continuity] A continuity issue results when a trace is not fabricated correctly; a break in this trace will result in an interrupted connection preventing the flow of electricity. Use the multimeter in continuity mode and place both probes at [start]. Move one probe towards [end], checking that the trace is continuous (beep throughout).
- For conductive thread, sew larger patches for connection pads; single strands may not be conductive enough.
- For copper tape, a common debugging technique is to lay additional copper over problem areas. A rule of thumb is to use continuous pieces of tape. To reduce connection errors and make copper tape more aesthetic, one can use a bone knife to press-down, reduce tarnish, and smooth copper tape.

EVALUATION

The goal of our formal user study was to conduct a usability evaluation of the tool, specifically observing how circuit design constraints influence the visual aesthetic and how fabrication assistance influences agency.

Participants

We recruited 10 participants (avg. 28 years, 7F, 3M) well-versed in visual design, but with no prior experience with circuit design. Proficiency was self-reported in a preliminary survey. Participants were recruited from a mailing list of Architecture, Art, and Design students at our institution and from the surrounding community via Craigslist.

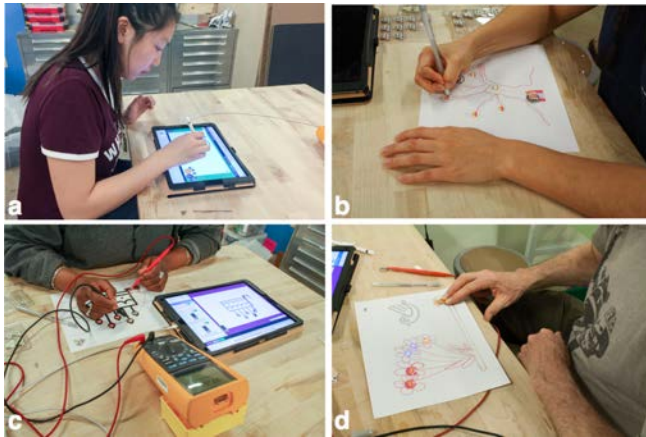


Figure 9. During the formal user study, users a) sketched their circuit ideas with the design tool, b) fabricated the circuit, c) checked circuit validity using a multimeter and, d) debugged their circuits by pressing on components.

Materials

We constrained our evaluation to a single circuit building material — silver ink pen was chosen due to its user-friendly pen form factor that is a tangible analog to the Apple Pencil. For the study, our electronics library was constrained to fixed set of finger-sized manipulatives: 5 Chibitronics LED stickers, and a single CR2032 coin-cell battery. We also exposed a set of SVG graphics shown in Figure 6 with different layout compositions (figurative, linear, radial, and random placement) in order to evaluate how users navigate circuit rules with spatial constraints.

Study design

Each participant was invited to individually meet with us in our studio space. Participants were paid \$20/hr; each session lasted two hours and consisted of a circuit and tool tutorial, a digital design and physical hand-fabrication task. We also conducted interviews before and after each session. Participants were also asked to think out-loud their reflections on tools and design process specifically vocalizing their design choices and shifts as they went through the workshop.

Warmup. We provided participants with relevant background information for understanding the primary concerns of circuit design and building. A brief introduction covered basic electrical design rules (e.g. connecting power and ground, avoiding shorts) and operation of equipment (drawing traces with a silver ink pen; checking resistance and voltage with a multimeter). Tutorial material was available as reference throughout the study.

Design Task. Participants were then given the task to design a circuit with five LEDs in parallel, with at least one background artwork incorporated for a period of 20 minutes. A five LED circuit provided a reasonable level of routing and creative challenge to be solved within 20 minutes. Parallel circuits also tend to create more routing complexity in an Aesthetic Circuit and require more creative solutions. If there were issues, they were asked to attempt to fix and iterate on their circuit design using features provided within the tool.

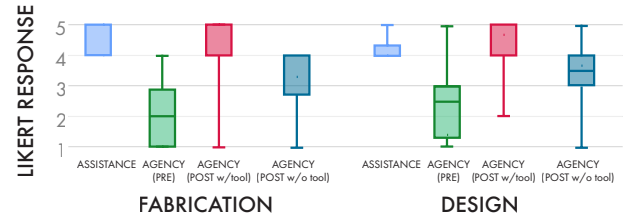


Figure 10. Tool evaluation responses. Overall, participants reported feeling more agency to create their own circuits after using Ellustrate, and felt that the tool assisted them with both design and fabrication.

Fabrication Task. Once successfully validated, our system produced fabrication instructions. A to-scale schematic was printed. Users were asked to fabricate their circuits using five circuit sticker LEDs. They were given 40 minutes to complete the task using fabrication and debugging instructions provided by the tool.

We asked participants to separately rate their experience with the design tool and the fabrication tool using five-point semantically anchored Likert questions (1=Strongly Disagree, 5=Strongly Agree):

- **Assistance (As):** The tool helped my circuit [designing/fabricating] process.
- **Pre-Agency (pA):** I feel capable of [designing/fabricating] a circuit before using the tool.
- **Post-Agency with Tool (ApT):** I feel capable of [designing/fabricating] future circuits with the tool.
- **Post-Agency without Tool (Ap):** I feel capable of [designing/fabricating] future circuits without the tool.

In particular, **ApT** describes the experience of designing a circuit with Ellustrate, while **Ap** generalizes to how Ellustrate may serve as a tool that enables lasting skills in Aesthetic Electronics design and fabrication.

RESULTS

All participants successfully completed their designs; some designs are represented here in Figure 11. We first report quantitative results and then discuss interview responses in the context of observations and insights from the study.

Before using Ellustrate, users expressed uncertainty and apprehension when asked to design and fabricate an Aesthetic Circuit, respectively (design: **pA** 2.4 ± 1.26 , fabricate: **pA** 2.1 ± 1.2). We were surprised to find that the mentioning of the word “circuit” elicited fear in some participants.

For both the design and fabrication tool, users felt that the tool had helped them on their design and fabrication processes (design: **As** 4.2 ± 0.42 , fabrication: **As** 4.4 ± 0.52). After using the tool, users felt capable of designing and fabricating Aesthetic Circuits in the future with the aid of the design tool (design: **ApT** 4.0 ± 1.22 , fabrication: **ApT** 4 ± 1.7), but slightly less capable of doing so without the aid of the tool (design: **Ap** of 3.4 ± 1.27 , fabrication: **Ap** 3.3 ± 1.3).

It was interesting to note that users with more visually complex designs that require multiple trial-and-error iterations to balance the visual design and electronic routing were more

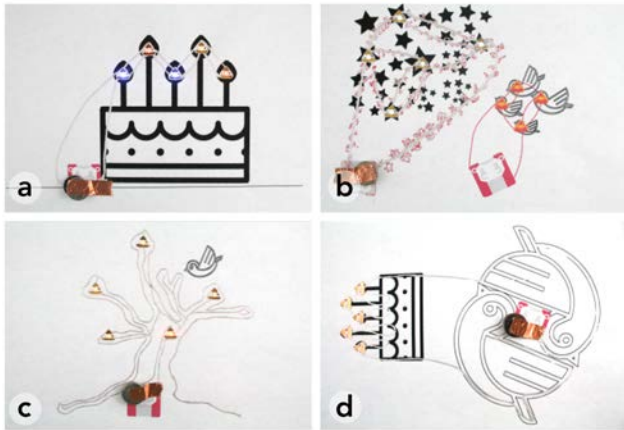


Figure 11. Completed circuits from the user study drawn in silver ink on paper. Circuit designs show examples of a) functionalist, b) mimetic, c) constructive, and d) symbolic marks.

likely to report higher reliance on designing Aesthetic Circuits without the tool in the future (lower **Ap**). In future work, we would like to investigate features that could further encourage users to create complex designs through iterations.

Design classifications

We distinguished three types of marks that characterize how participants navigated around circuit rules to create their visual designs, as detailed below:

Functionalist: While all participants positioned their LEDs in semiotically relevant places (e.g. matching the triangular shape of the LED footprint with the candle flames, placing LEDs at the tips of the branches), some participants preferred a functionalist aesthetic, connecting electrical components using straight lines that minimized distance and distractors. Figure 11a shows an example of a functionalist design.

Mimetic: Other designs adhered to the design language of the chosen graphical elements. An example of a mimetic design is shown in Figure 11b, where the participant drew traces as a collection of twinkling lights, extended the visual texture of the imported star graphic. In these scenarios, because participants mimic the existing design language, the choice of graphic highly influences the aesthetics of a participant’s final design.

Constructive: In contrast to functionalist and mimetic lines, other participants drew objects wholly outside of existing graphical language. Notably, Figure 11c shows a circuit as a tree, where the user carefully interleaved electrically-opposite strokes to form the branches and roots; the graphic in this instance (a bird) is used solely to contextualize the tree.

Participant #156: I thought of something where I can branch out the wires, and I thought “bird and branches.”

Symbolic: Some participants went beyond using lines as a means of connecting wires, but instead as a method of ascribing meaning. Figure 11d shows a “yin-yang” formed by two rotated bird forms. Traces and other footprints then conform to the meaning established by the birds. With metaphorical lines, participants satisfied not just two criteria: a) functional

requirements of a trace in a circuit and b) aesthetic considerations, but also developed a “language” or a system of meaning based on the traces. We observed users using this “language” to tell a story with their circuit design, which was also observed in prior circuit sketching workshops [13].

Participant #499: The birds represent ying and yang, and the battery in the center represents the energy coming out of them ... the stars are tied together with twinkle light ropes, and the birds are flying towards the pretty lights.

OBSERVATIONS AND INSIGHTS

In the following section, we report important insights derived from our user study.

Translation between digital and physical mental models

We found that participants with no circuit experience relied heavily on the interface mechanisms used to convey circuit rules, adopting the visual vocabulary of the circuit design interface (e.g. “red and black” vs. “positive and negative”).

Participant #499: I know there two silver traces can’t cross - they are red and black and I need to be careful to not draw them too close to each other.

Some users memorized the colors of the traces in their designs, and transferred that representation to their physical circuit fabrication. This observation shows opportunities in injecting more important circuit design concepts as visual representations, such as current as flowing water, within the digital design tool.

Templating, learning, and improvising

We were encouraged to find that participants developed a sense of agency and formed early material fluency and electronic fluency during the study sessions. When first fabricating circuits, participants found comfort and safety in the step-by-step fabrication guide. The format of a list, with additional debugging tips as an expandable-list feature, were particularly appreciated.

Participant #081: I like that the list of steps is very clear, and the debugging tips are tucked away until you indicate that you have a circuit problem.

However, as they progress through the process, some found the format too rigid and wished to learn more about the rationale behind the guided steps.

Participant #554: There are obviously some rules behind where to put the multimeter probes to debug, I would like the tool to explain that to me so that I can do it by myself.

This friction behind hidden rationales caused some participants to improvise new ways to fabricate and debug by relying on their own intuitions and bypass certain steps within the guide. For example, most users dislike waiting 60 seconds for the silver ink to dry, so some started blowing on the ink to get the ink to dry faster or moved the paper around to distinguish color differences between dry and wet ink. Users who triggered an error message regarding high resistance while digitally designing drew the silver traces during fabrication with greater care in order to prevent breaks or high resistance. In-depth learning occurred at different points of the process

for each participant. We were encouraged by the diversity of learning styles and the early development of fluency, and we see this as an opportunity to create more customizable instructions and learning materials for users in the future.

LIMITATIONS

While we have highlighted the contributions of Ellustrate in the development of Aesthetic Circuits, there are several limitations to the current state of the design tool.

Electronic and material library

We chose to focus on including several basic electronics and materials in our current tool. We included Chibitronics CircuitStickers and LEDs of various packages in the electronics library, and silver ink, graphite ink, and copper tape in the material library. These components and materials were chosen because they were commonly used in circuit craft making, but they are far from being an exhaustive list of electronics that can be used in an Aesthetic Circuits. If Ellustrate can successfully promote a literacy in creating Aesthetic Electronics, we imagine the library would have to greatly expand. The footprint of a wide variety of interactive electronics, such as pressure sensors, microphones, IR sensors, could be included. Moreover, some physical electronics that can be created directly with conductive painting, such as capacitors, paper speakers, and strain gauges, could be included in the library as well (where their electronic properties can be simulated dynamically with the design).

Circuit drawing capability

The circuit drawing capability of Ellustrate could be improved on both the aesthetic drawing and circuit simulation front. Currently, the digital form factor, although more fluid than expected, left much to be desired from pen and paper. Users cited resolution and accidental markings (from digital artifacts) as major concerns. The number of drawing features within the tool was also significantly fewer than what is available in a visual designer's repertoire. Circuit decomposition also faces unique problems as Aesthetic Circuits often contains a high number of trace intersections that are common drawing techniques such as cross-hatching. Ellustrate currently has difficulty validating circuits that contain a high number of intersections, which limits the complexity of artwork that could be created with the program.

DISCUSSION AND FUTURE WORK

Beyond the design and fabrication of Aesthetic Circuits, we envision Ellustrate to initiate in a broader conversation of the enablement of Aesthetic Electronics. In this section, we will discuss a few directions that we envision Ellustrate to aid in achieving this goal.

Material properties for design

Technological fluency, defined as “the ability to understand, use, and assess technology beyond its rote application”, is seen as one of the fundamental quality that affords creativity [18]. As the landscape of interaction design broadens to include a wide range of materials, including living cells, polymer, and even water [31, 17, 22], a fluency in material properties becomes increasing important in creating innovative tangible interactive platforms. Ellustrate aims to promote the

exploration of fundamental material properties by providing a digital platform for users to explore the electrical and visual artifacts of conductive materials - something more commonly thought of as digital in function (i.e. connected vs. disconnected) by non-experts. Within Ellustrate, we have shown how users can explore the changes in resistance and visual aesthetics as they widen and lengthen conductive traces or change the material used. In the future, we envision Ellustrate to incorporate the simulations of more nuanced and advanced electrical properties (i.e. impedance and inductance). Furthermore, existing trace routing practices such as using trace-assist to inform valid paths in electrical designs can be leveraged as a stencil to guide aesthetic decisions while maintaining electrical validity. Beyond understanding the nature of conductive materials, we hope to initiate a design conversation by disrupting the perception of an object that is well-defined - an electrical connection does not necessary take on the shape of a wire, but it could be something with many variables that can be manipulated. We believe that Ellustrate could be used as a tool to democratize the critical thinking about materials and enable the exploration of the next creative tangible interface.

Online community

Ellustrate could have great impact on the hardware sketching practice as we develop an online community for users. While users could follow current sharing practices by contributing circuit designs, we see opportunities for users to contribute tacit technical knowledge inherent in a material-rich process. This might manifest as step-specific tips, questions, and deviations in the fabrication and debugging process. The framework of the digital tool - design, fabricate, and debug - accompanied with electronic property analysis which is usually hidden from users could be expanded to include other Aesthetic Electronic input and output elements that are common to interaction design (i.e. capacitive sensors, strain gauges) as well. We envision the Ellustrate community to be capable of supporting users with richly diverse aesthetic styles, electronic experiences, and learning and teaching styles.

CONCLUSION

In this paper, we presented Ellustrate, a digital tool for designing and fabrication Aesthetic Circuits. We demonstrated its capability to assist in creating circuits with different conductive and non-conductive materials - silver pen, graphite paint, conductive thread, fabric, and paper. We detailed algorithms specially designed to decompose and extract relevant traces for circuit analysis. Ellustrate was designed based on formative interviews with experts and pilot studies with visual designers in order to address common challenges with Aesthetic Circuit designs. We also performed formal user studies to evaluate the design and fabrication of circuits enabled by the design tool. We hope that Ellustrate will be adopted by practitioners from diverse fields and inspire a suite of creative Aesthetic Circuit designs.

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